Geoacoustic Inversion and the Evaluation of Model and Parameter Uncertainties

W.S. Hodgkiss and P. Gerstoft
Marine Physical Laboratory
Scripps Institution of Oceanography
La Jolla, CA 92093-0701
phone: (858) 534-1798 / (858) 534-7768 fax: (858) 822-0665
email: whodgkiss@ucsd.edu / gerstoft@ucsd.edu

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LONG-TERM GOALS

The development of new geoacoustic inversion methods, their use in the analysis of shallow water experimental data, and evaluation of geoacoustic model and parameter uncertainties including the mapping of these uncertainties through to system performance uncertainties.

OBJECTIVES

The development of new geoacoustic inversion procedures for use into the kHz frequency regime, the development of methods for estimating the entire posteriori probability densities of the geoacoustic parameters being investigated along with the mapping of these parameter uncertainties through to characterizations of applied interest (e.g. transmission loss), and the demonstration of their use in the analysis of data collected during the Shallow Water 2006 (SW06) experiment.

APPROACH

Geoacoustic inversion involves a number of components: (a) representation of the ocean environment, (b) the inversion procedure selected (e.g. genetic algorithm or simulated annealing) including the forward propagation model implemented, and (c) the estimation of uncertainties associated with the parameter estimates. The latter is critical to facilitate the mapping of these uncertainties into characterizations of applied interest including the prediction of total system performance.

Substantial experience exists in the application of full-field geoacoustic inversion methods. These have been implemented in a number of geometries (e.g. fixed vertical and horizontal arrays, towed arrays, and sonobuoys) and have been shown to work well at low frequencies (< 1 kHz). The application of these methods at higher frequencies (into the few kHz frequency regime) is at an early stage. New methods are required which are robust to modest geoacoustic heterogeneity (seafloor parameters as well as bathymetry) and temporal fluctuations (sound speed structure, surface waves, and array dynamics).

The reporting of geoacoustic parameter estimates without their associated uncertainties is of limited value. Of substantial greater utility is the complete *a posteriori* probability density (in general, the joint density between all parameters being estimated). One significant benefit of obtaining accurate *a posteriori* densities of the geoacoustic parameters is the potential to map these through to

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14. ABSTRACT
The development of new geoacoustic inversion methods, their use in the analysis of shallow water experimental data, and evaluation of geoacoustic model and parameter uncertainties including the mapping of these uncertainties through to system performance uncertainties.

15. SUBJECT TERMS

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characterizations of applied interest (e.g. transmission loss) in order to quantify those uncertainties as well.

The Shallow Water 2006 experiment took place in July-September 2006 on the outer edge of the New Jersey continental shelf in approximately 80 m deep water. Both narrowband and broadband transmissions (source tows and stations) were made over a wide range of frequencies (50 Hz – 5 kHz) including detailed measurements of seafloor structure and water column variability. These data are available for geoacoustic inversion purposes and the investigation of how nuisance parameter uncertainty (e.g. water column sound speed variability) couples into seafloor parameter uncertainty.

WORK COMPLETED

A method has been developed for estimating transmission loss (TL) that incorporates uncertainties in the acoustic environment. Specifically, an approach has been derived and validated for the statistical estimation of TL based on the posterior probability density of environmental parameters obtained from the geoacoustic inversion process [1,3]. Validation made use of ASIAEX East China Sea source tow data collected with a vertical array. Recently, this approach has been used to validate TL predictions from a completely different environment using horizontal towed array data from a fixed source [6].

Quantifying uncertainty for geoacoustic parameter estimates requires estimation of the uncertainties in the data due to both ambient noise as well as modeling errors with the latter accounting for simplistic assumptions about seafloor structure, water column variability, range dependencies, etc. [2]. Both of these combine in a total error variance that describes the data uncertainty. The impact of correlated data errors on matched-field geoacoustic inversion has been explored in simulation [4].

The Shallow Water 2006 experiment took place in August-September 2006. Initial analysis has focused on the effect of ocean sound speed uncertainty on geoacoustic inversion along a relatively range-independent bathymetric track [7]. Significant sound speed variations were observed at the source and receiving array and this motivated investigating several environmental parameterizations for the inversion that incorporated data from eight tonals between 53 Hz and 703 Hz.

Additional work has developed the theory for use of signals recorded from a vertical line of sources to infer the Green's function between two receivers [5] and has explored the impact of spatial aliasing on the use of vertical array coherent ambient noise processing for estimation of seafloor layering [8].

RESULTS

An approach has been developed and validated for mapping uncertainty in geoacoustic parameter estimates into uncertainty in predicted transmission loss [1,3]. Recently, this approach has been used to validate TL predictions and their uncertainties from a completely different environment and source / receiving array geometry [6]. The data was collected by the NATO Undersea Research Centre (NURC) in November 2000 north of Elba Island, Italy.

The observed data corresponds to a stationary source approximately 55 m deep and 750 m range from the first hydrophone of a horizontal line array (HLA) being towed at 4 knots and 55-65 m depth in 115 m deep water. The HLA consisted of 128 hydrophones with 2 m spacing. A sequence of 2 s LFM sweeps covering 150-500 Hz were transmitted by the source every 15 s. The band 300-500 Hz was used in the inversion.

The overall experimental geometry and baseline geoacoustic model are shown in Fig. 1. A CTD taken immediately before the data was collected shows a slight positive gradient for most of the water column except near the bottom where there was a sharp decrease in sound speed.

A Markov chain Monte Carlo (MCMC) procedure is employed in the inversion process to sample the posterior probability density of all geometric and geoacoustic parameters. Then these sampled parameters are mapped to the transmission loss domain where a full multidimensional probability distribution of TL as a function of range and depth is obtained. From this TL probability distribution, all relevant statistics of TL can be obtained (e.g. median, percentiles, and correlation coefficients).

Based on the geoacoustic inversion results, the predicted TL and its variability are estimated and then compared with the measured TL.

Using this procedure, Fig. 2 shows the posterior distribution of TL vs. range at 300 Hz for a receiver depth of 60 m. Fig. 2(a) shows the contour of predictive distribution of TL vs. range. Gray levels represent the probability density. Darker shades mean higher probability of observing the predicted TL value. Predictive distributions at two different ranges are shown in Figs. 2(b) and 2(c) that correspond to regions of destructive and constructive interference, respectively. Since the distribution of TL is often poorly approximated by a normal distribution, the central tendency (median) and spread of the TL distribution (5^{th} and 95^{th} percentiles or 90% credibility interval) are indicated. Fig. 2(d) summarizes the predictive distributions by the median (heavy line) and the 90% CI (gray area). This is a practical way to convey the uncertainty in TL.

Predictive distributions of TL are compared with actual TL observations (crosses) in Fig. 3 for a receiver depth of 55 m and frequencies 300, 400, and 500 Hz. The median of the predicted TL (solid line) is shown together with the 90% credibility interval (gray area). Fig. 3(a) shows the initial prediction based on a fixed source depth of 52.3 m. The results are poor due to not accounting for variability in the source depth over the observation period. Fig. 3(b) revises these predictions by including modest fluctuations in source depth. The results are improved significantly with over 80% of the observed TL values falling within the 90% CI. Lastly, Fig. 3(c) further explores the impact of modest water column sound speed variability where the predictions in Figs. 3(a) and 3(b) assumed the sound speed was known. In general, there is good agreement with the percentage of observed TL data points within the credibility intervals shown in Figs. 3(b) and 3(c).

IMPACT / APPLICATIONS

Geoacoustic inversion techniques are of general interest for the estimation of waveguide parameters thus facilitating system performance prediction in shallow water. Natural transition paths for these results will be the Intelligence, Surveillance, and Reconnaissance and Information Operations Program Office (PMW-180) and the Naval Oceanographic Office.

RELATED PROJECTS

This project is one of several sponsored by ONR Code 321OA to participate in the Shallow Water 2006 experiment and participate in the analysis of the resulting data.

PUBLICATIONS

[1] P. Gerstoft, C-F. Huang, and W.S. Hodgkiss, "Estimation of transmission loss in the presence of geoacoustic inversion uncertainty," IEEE J. Oceanic Engr. 31: 299-307 (2006). [published, refereed]

[2] C-F. Huang, P. Gerstoft, and W.S. Hodgkiss, "Uncertainty analysis in matched-field geoacoustic inversions," J. Acoust. Soc. Am. 119: 197-207 (2006). [published, refereed]

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[6] Y. H. Goh, P. Gerstoft, W.S. Hodgkiss, and C-F. Huang, Statistical estimation of transmission loss from geoacoustic inversion using a towed array, J. Acoust. Soc. Am. 122(5): 2571-2579 (2007). [published, refereed]

[7] C-F. Huang, P. Gerstoft, and W.S. Hodgkiss, "Effect of ocean sound speed uncertainty on matched-field geoacoustic inversion," J Acoust. Soc. Am. EL (submitted, 2007).

[8] P. Gerstoft, W.S. Hodgkiss, M Siderius, C-F. Huang, and C.H. Harrison, "Impact of spatial aliasing on the use of coherent ambient noise processing for estimation of seabed layering," J Acoust. Soc. Am. (submitted, 2007).

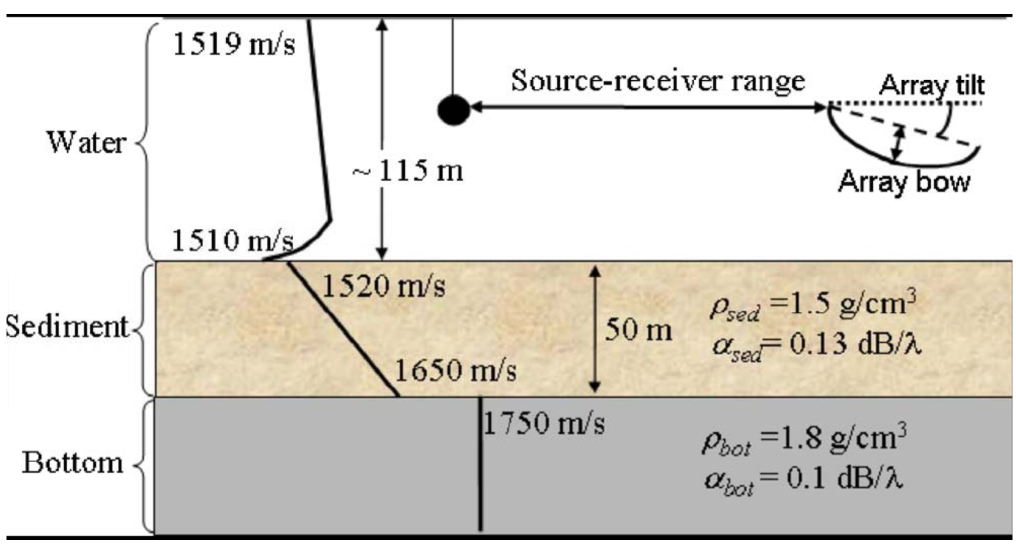

Figure 1. The overall experimental geometry and baseline geoacoustic model for the data collected north of Elba Island, Italy.

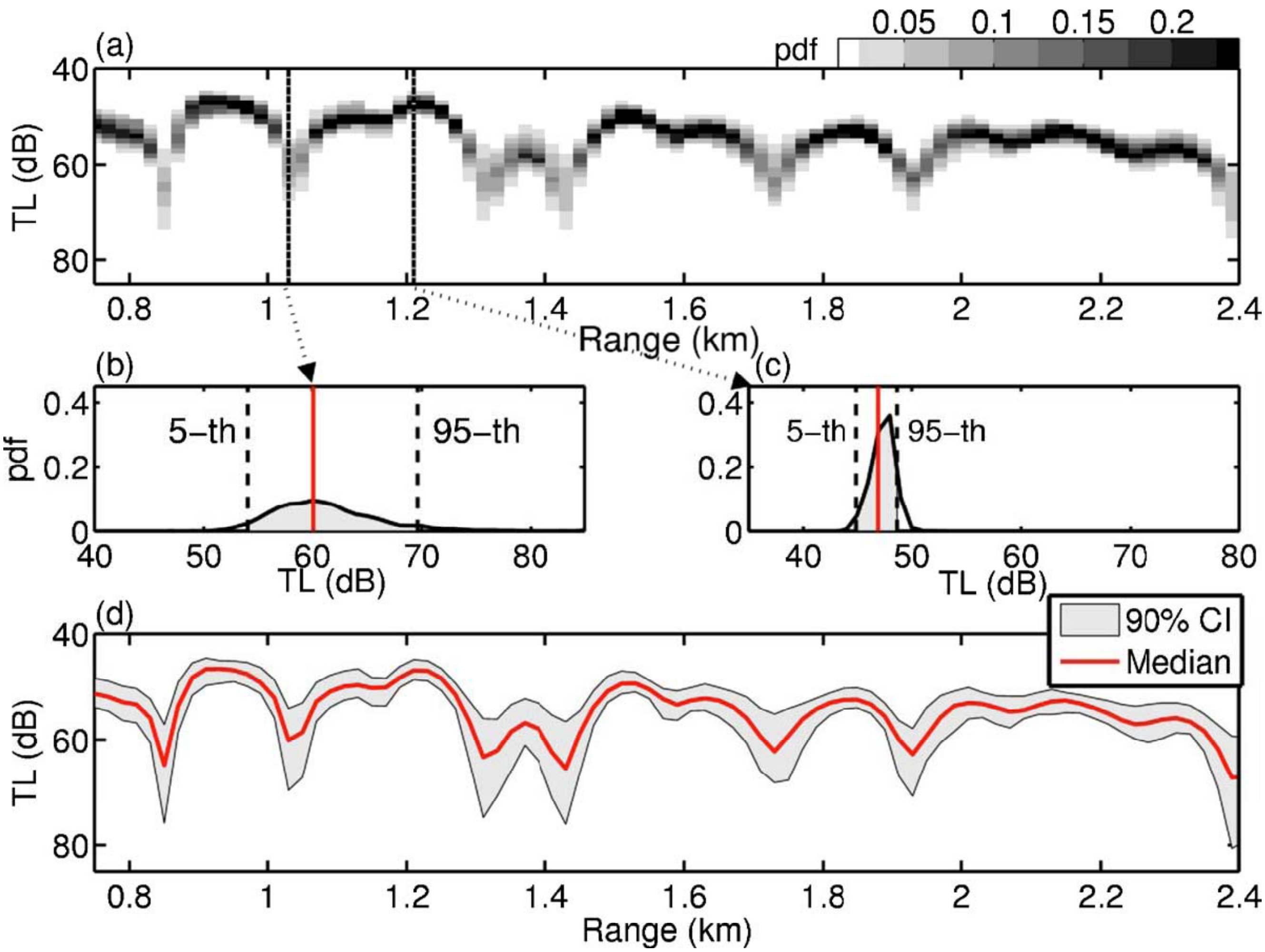

Figure 2. Posterior distribution of TL vs. range at 300 Hz for a receiver depth of 60 m: (a) Contour of posterior distribution for TL vs. range. (b) and (c) Posterior distributions of TL at two different ranges. These correspond to cuts (vertical dashed lines) through the contour. (d) Statistics of the predicted TL vs. range. The solid line with gray area around shows the median and the 90% credibility interval of the posterior distribution.

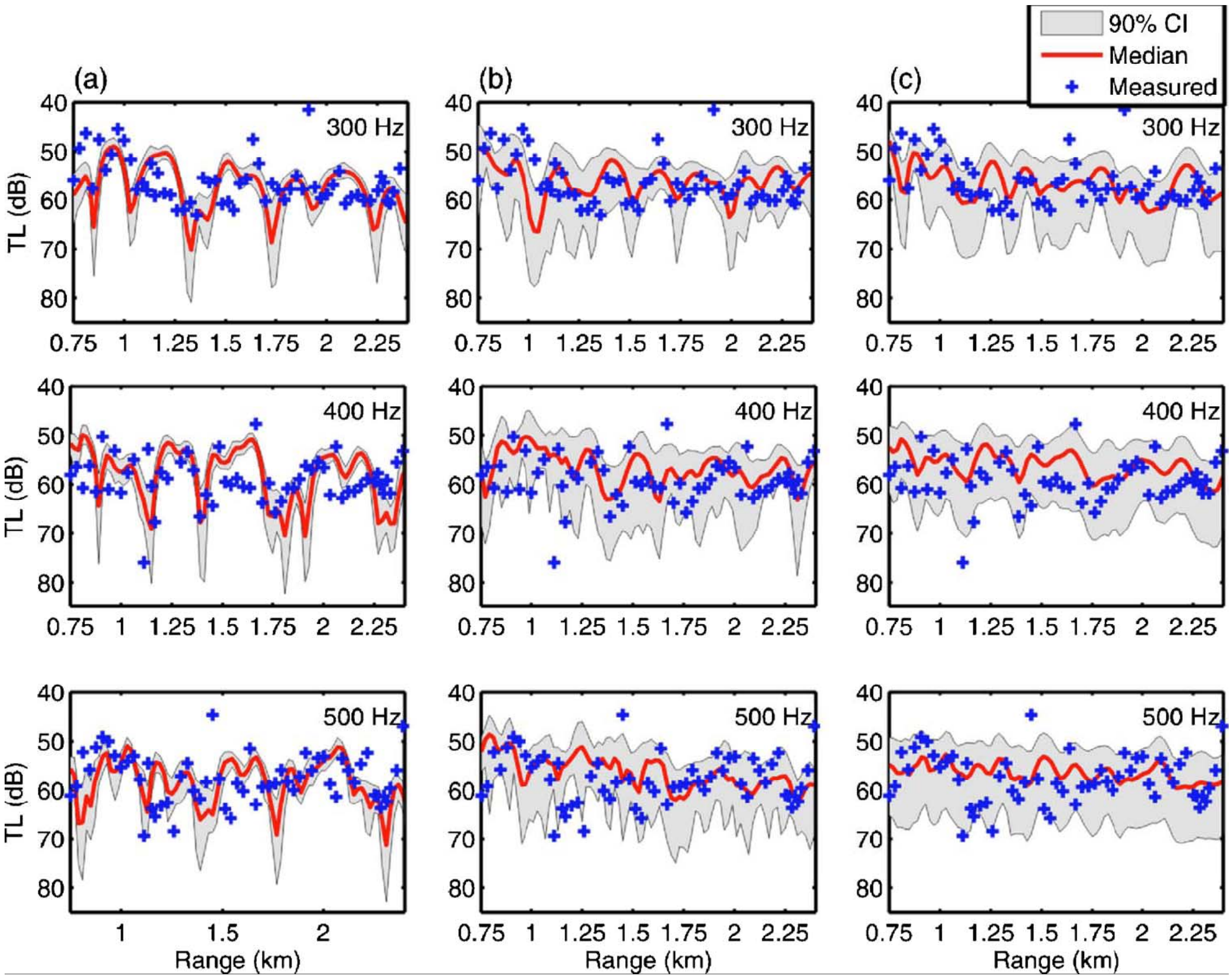

Figure 3. Predicted and measured TL (crosses) for a receiver depth of 55 m and frequencies 300, 400, and 500 Hz. The median of the predicted TL (solid line) is shown together with the 90% credibility interval (gray area). (a) Initial prediction. (b) Prediction with uncertainty introduced in source depth. (c) Prediction with uncertainty introduced in sound speed profile.